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[54] **EXTENDIBLE-RANGE VOLTAGE CONTROLLED OSCILLATOR**

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Attorney, Agent, or Firm—Wayne P. Bailey

[21] Appl. No.: **264,863**

[22] Filed: **Jun. 23, 1994**

[51] Int. Cl.⁶ **H03B 5/00**

[52] U.S. Cl. **331/177 R; 331/57; 331/107 R**

[58] Field of Search 331/8, 10, 11, 331/34, 57, 107 R, 177 R; 327/261, 392, 264, 272, 278, 285, 290

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[57] ABSTRACT

A circuit design extending the range and linearizing the transfer characteristic of a fast voltage controlled oscillator (VCO). In addition, a multi-range VCO is described. Range extension is achieved by modifying the delay cell of a current controlled ring oscillator. The VCO transfer characteristic is linearized by piece-wise linear current control added to the delay cell. Additionally, a VCO capable of multi-range operation is provided. With the addition of multiple current sources which control booster inverter current, and by selectively enabling the additional current sources, a VCO with multiple frequency ranges can be achieved.

12 Claims, 16 Drawing Sheets

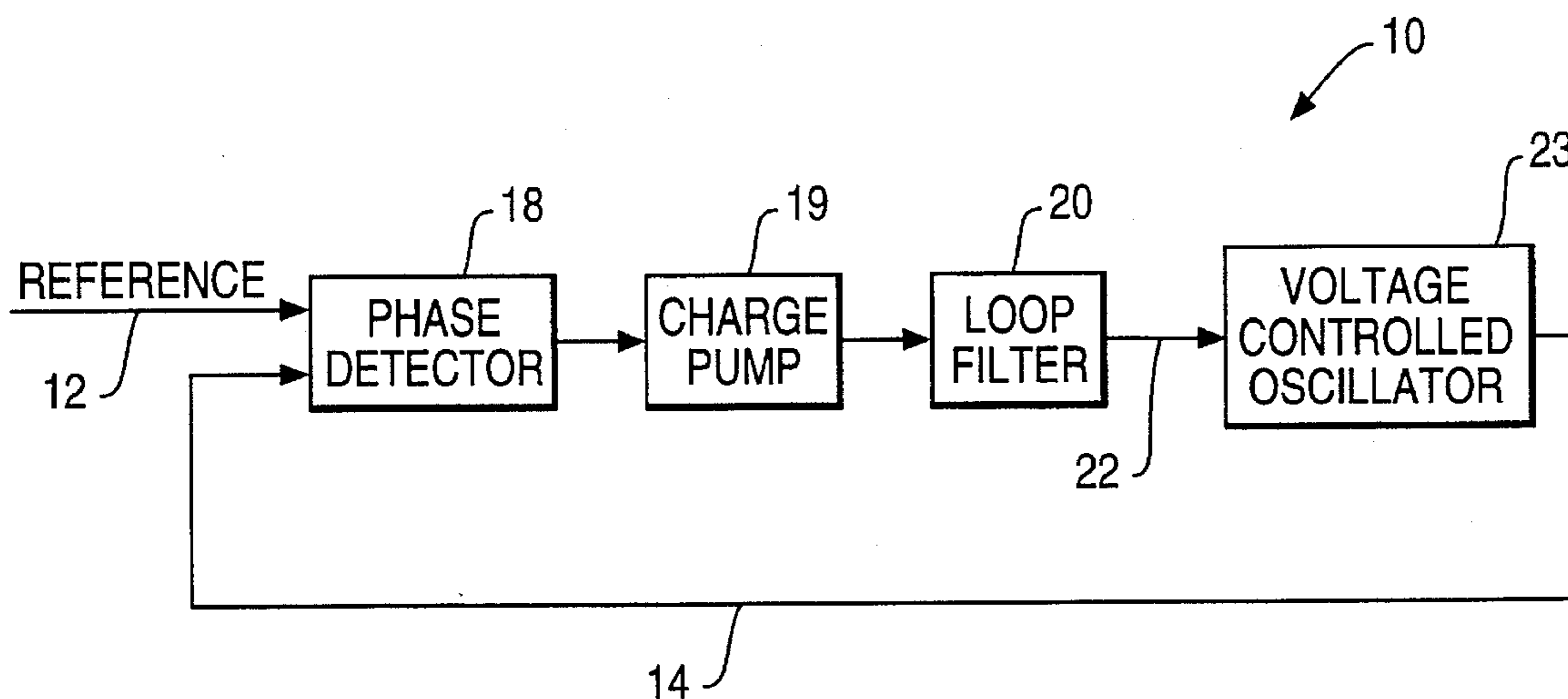


FIG. 1

PRIOR ART

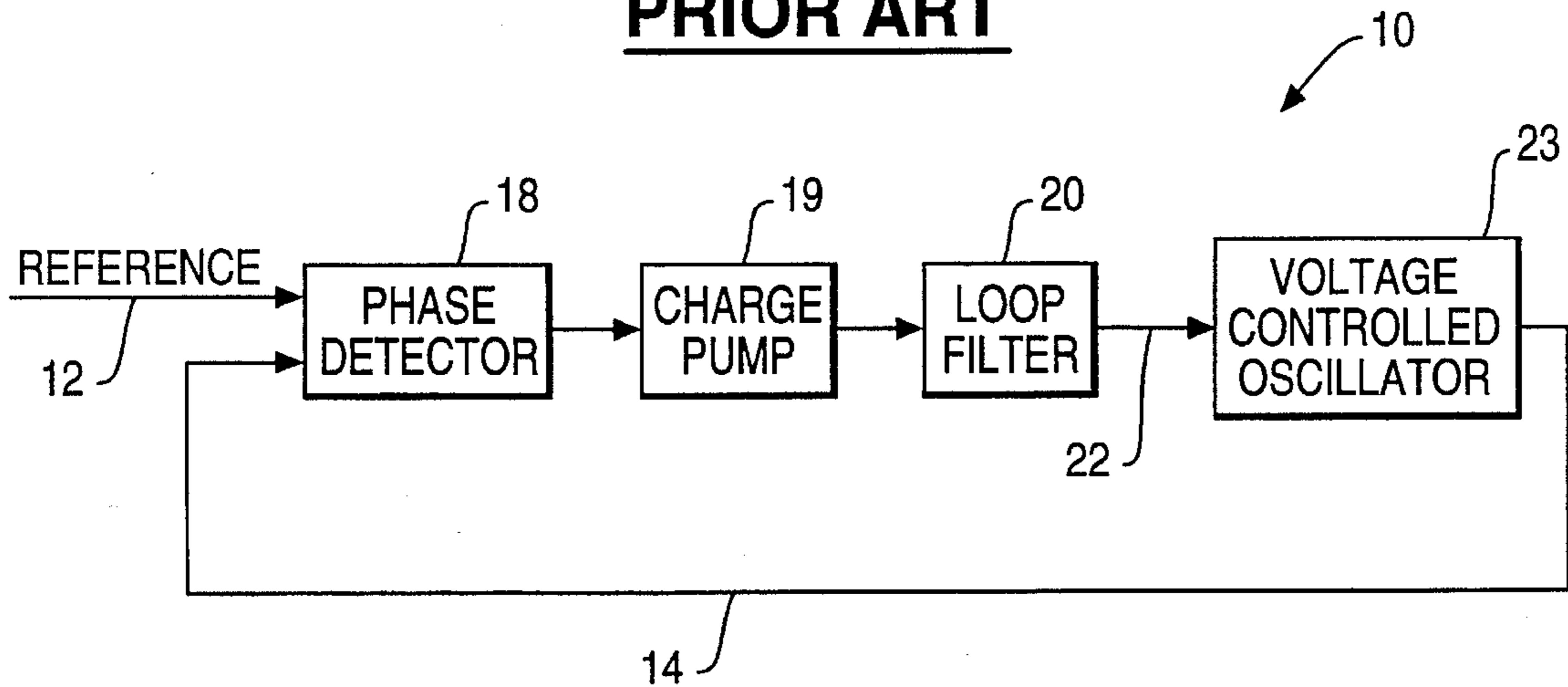


FIG. 2

PRIOR ART

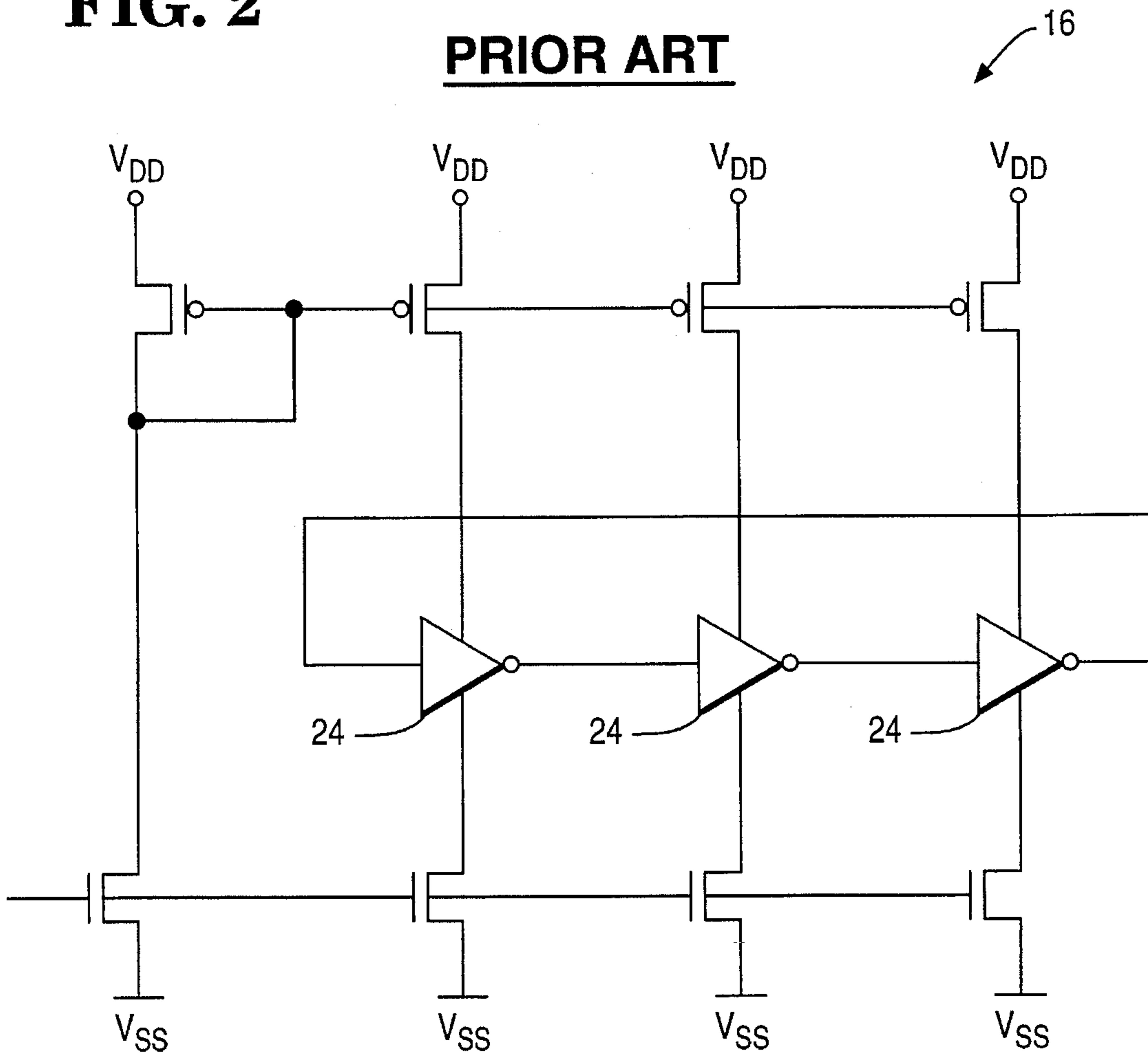
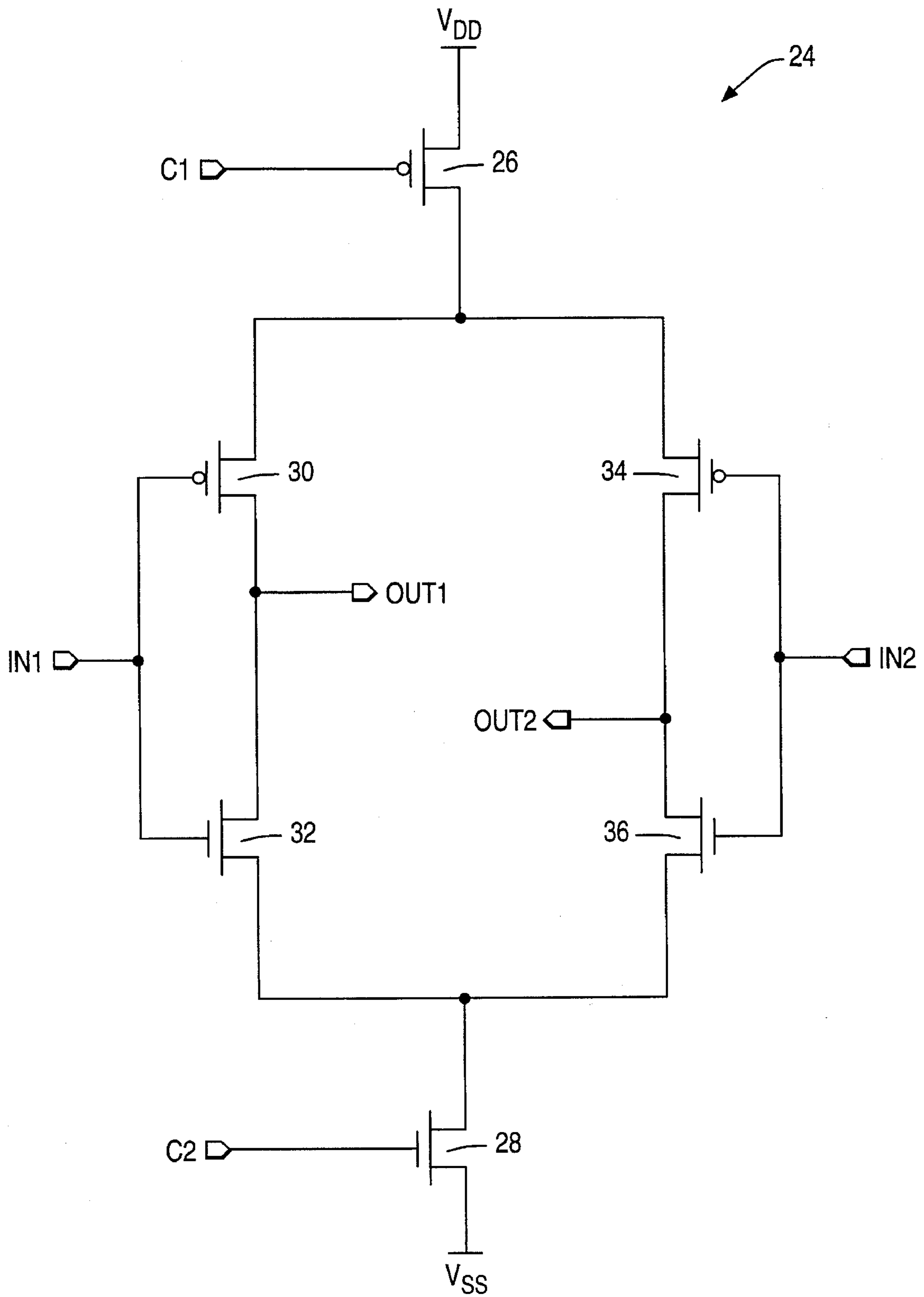


FIG. 3



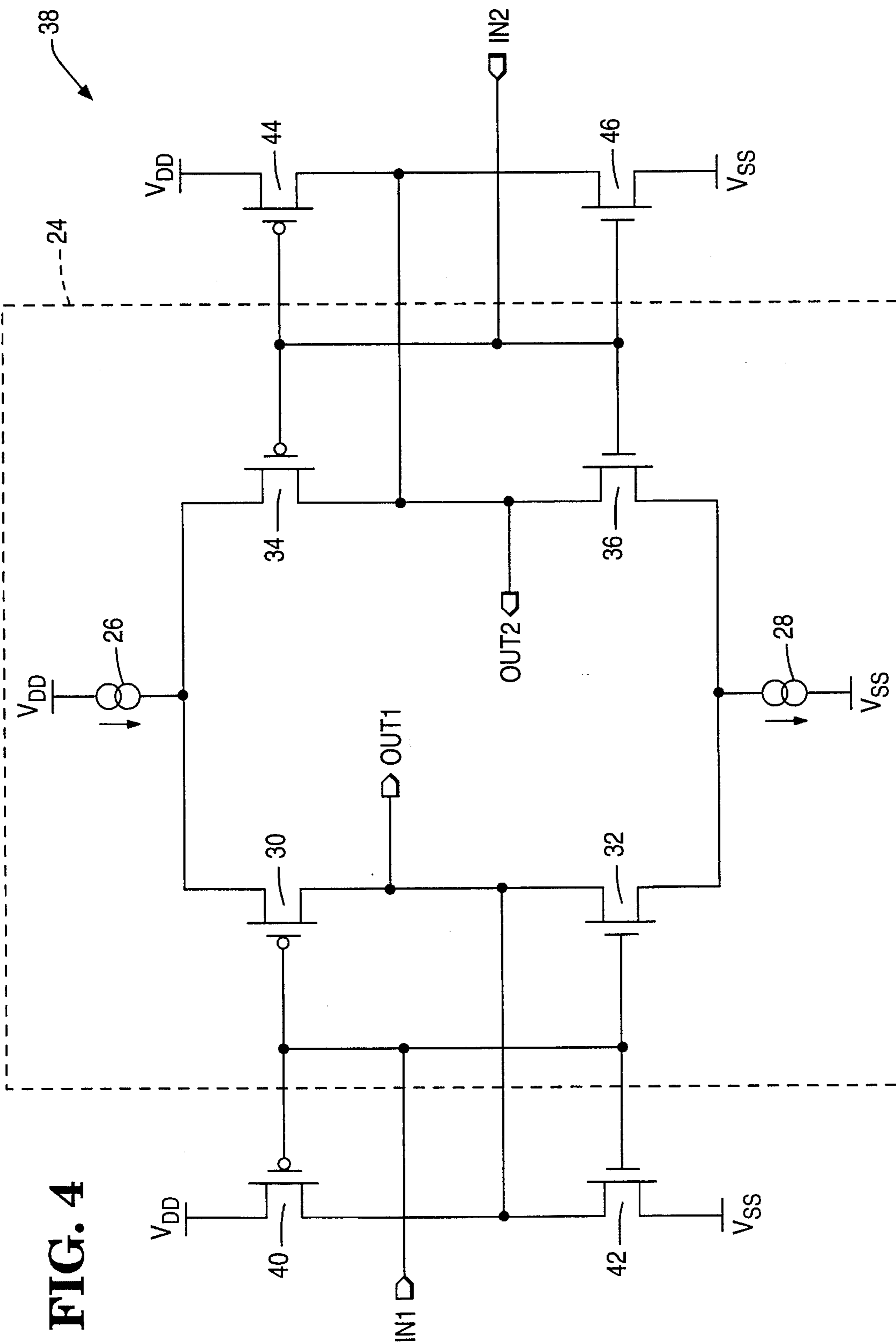


FIG. 4

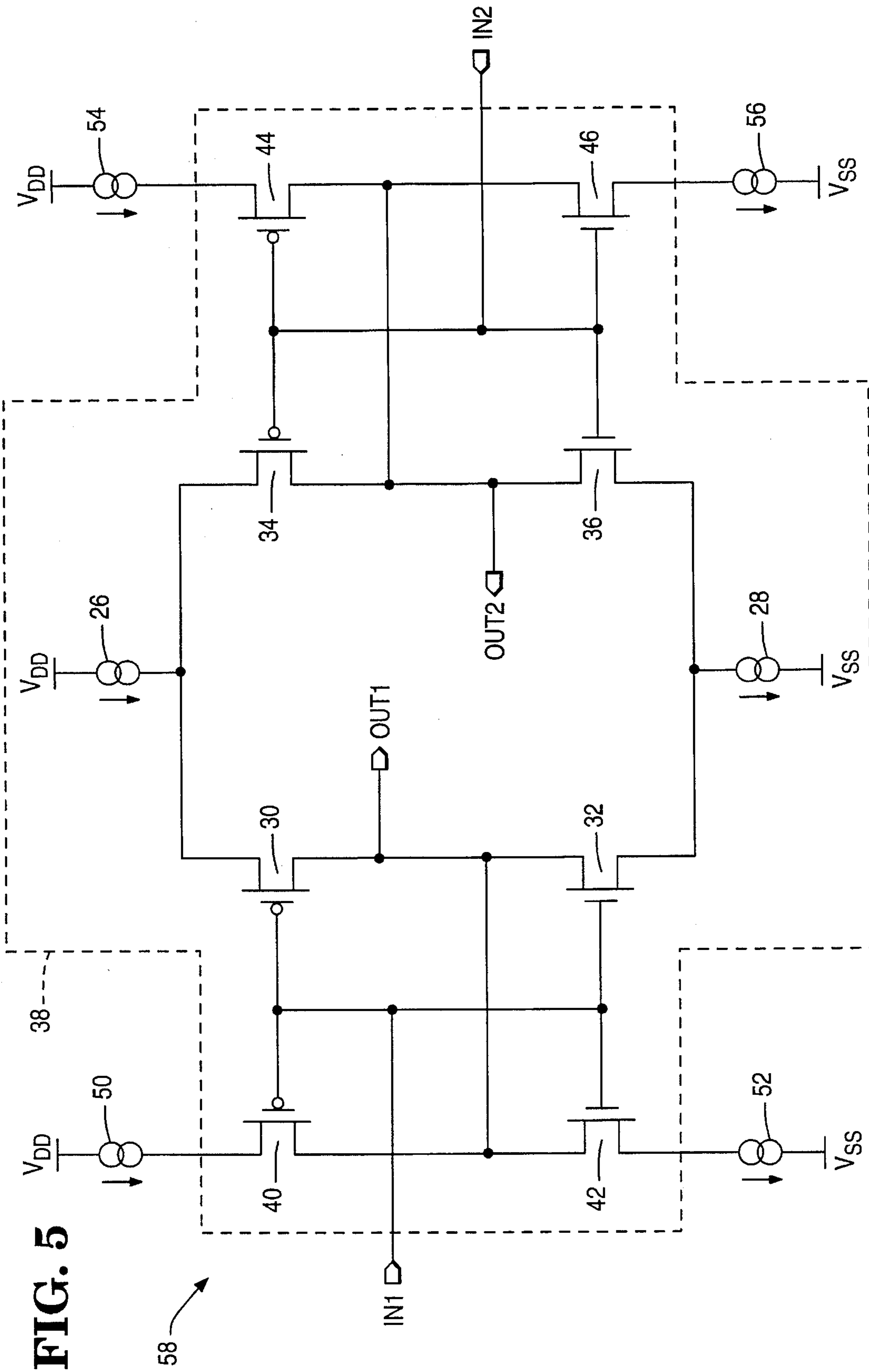
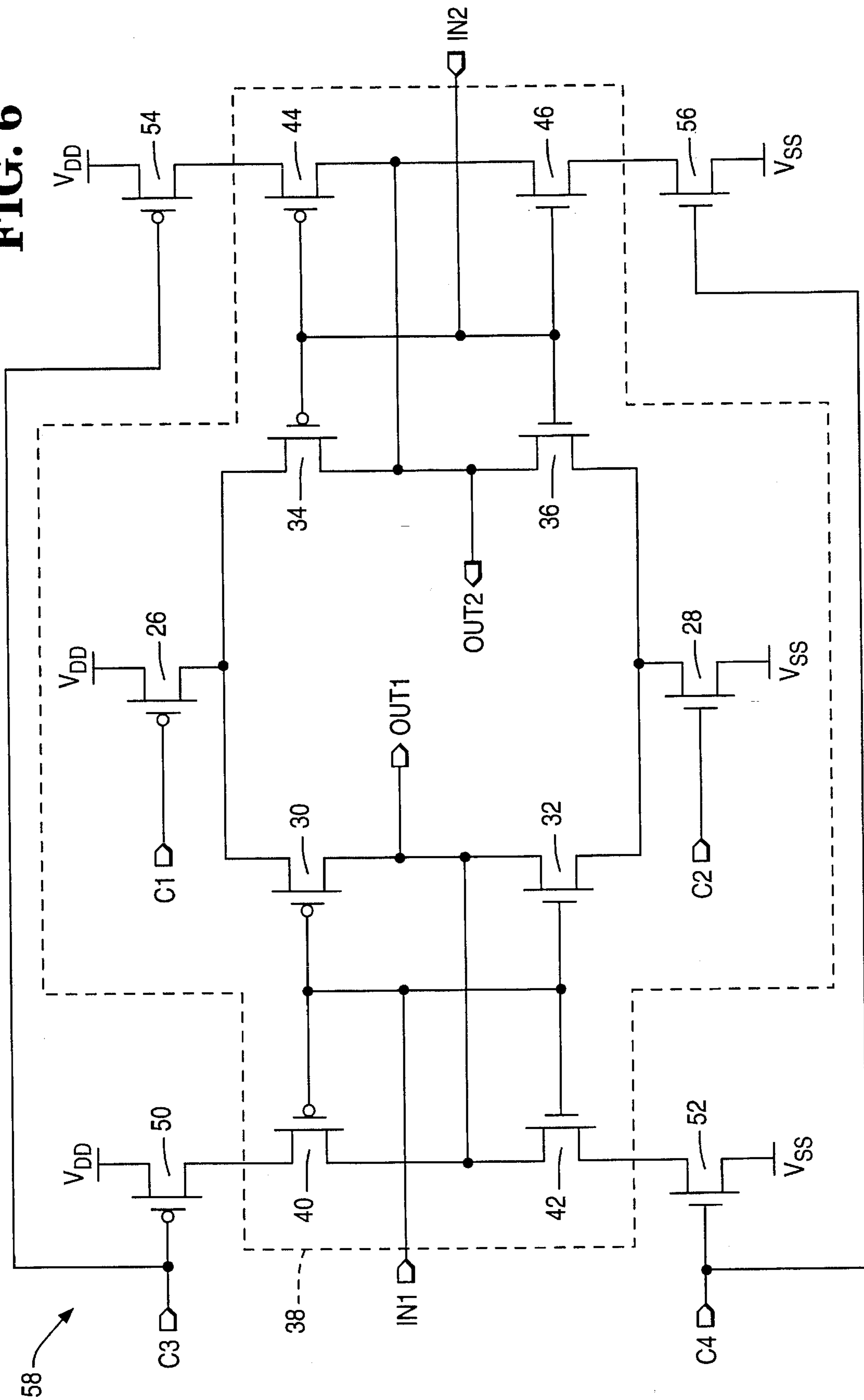


FIG. 5

FIG. 6



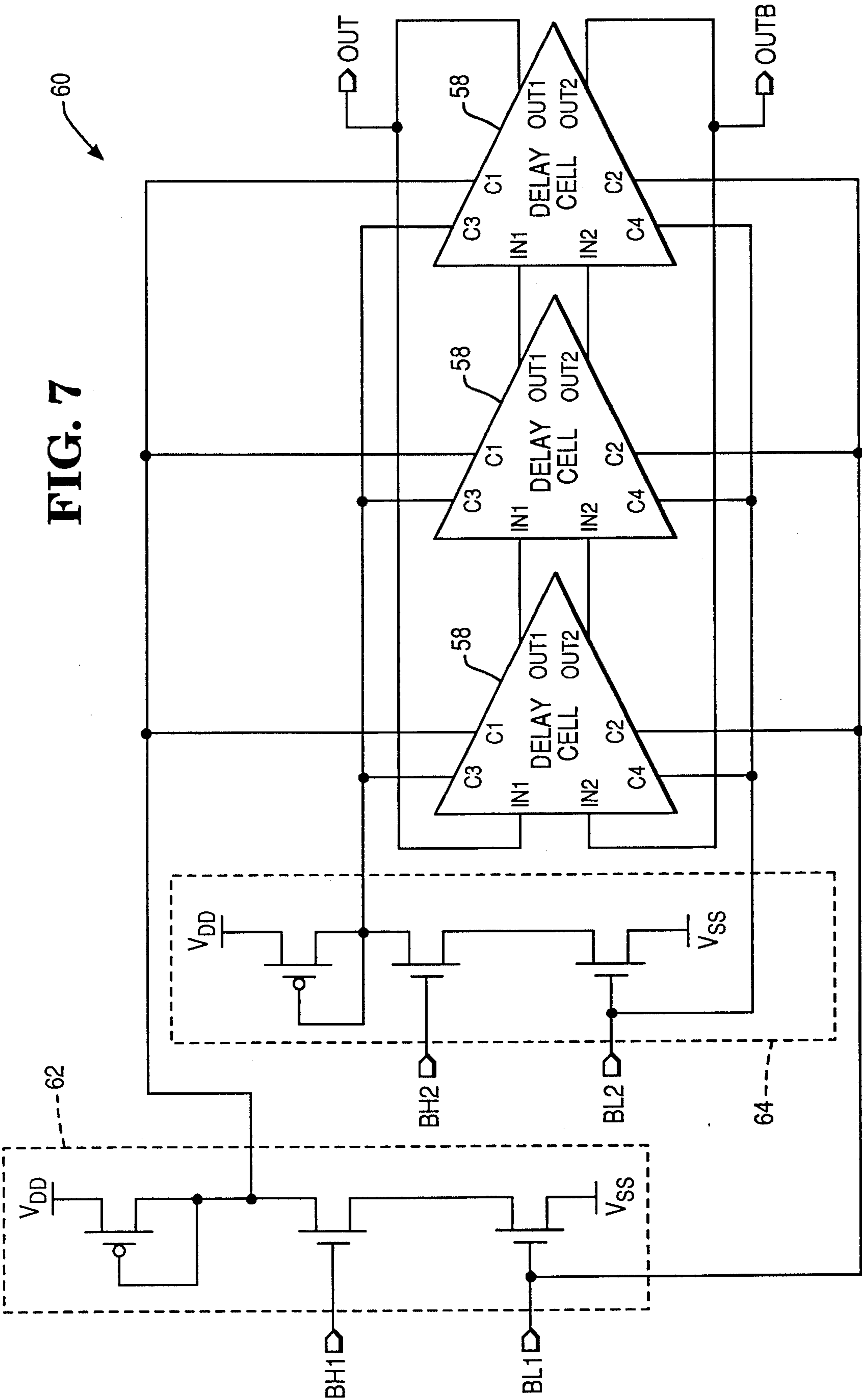


FIG. 7

60

62

64

BH1

BL1

BH2

BL2

58

58

58

VDD

VSS

VDD

VSS

OUT

OUTB

IN1
IN2
C1
C2
C3
C4

IN1
IN2
C1
C2
C3
C4

IN1
IN2
C1
C2
C3
C4

IN1
IN2
C1
C2
C3
C4

IN1
IN2
C1
C2
C3
C4

IN1
IN2
C1
C2
C3
C4

OUT1
OUT2

OUT1
OUT2

OUT1
OUT2

OUT1
OUT2

OUT1
OUT2

OUT1
OUT2

OUT1
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OUT1
OUT2

OUT1
OUT2

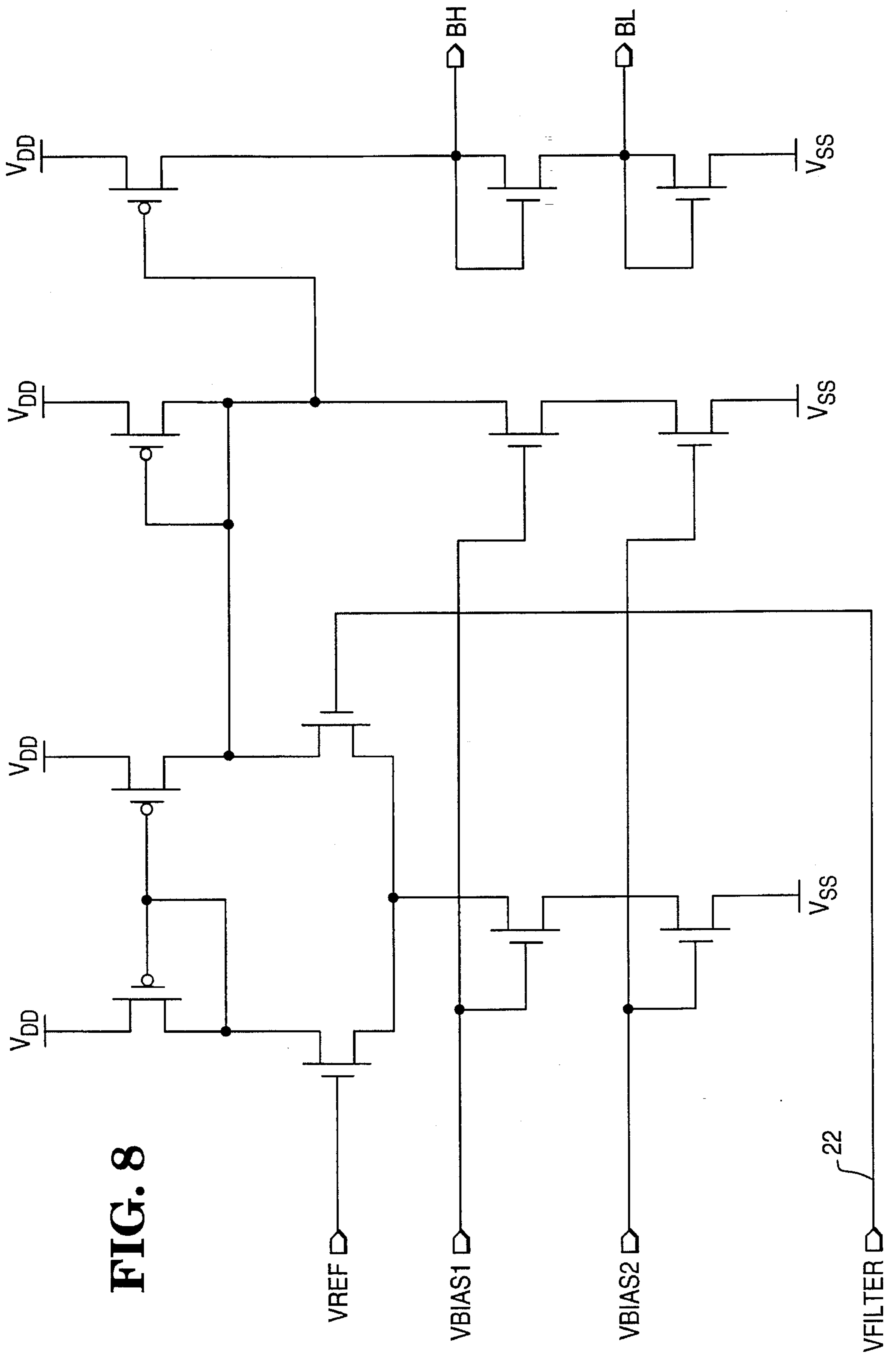


FIG. 8

FIG. 9

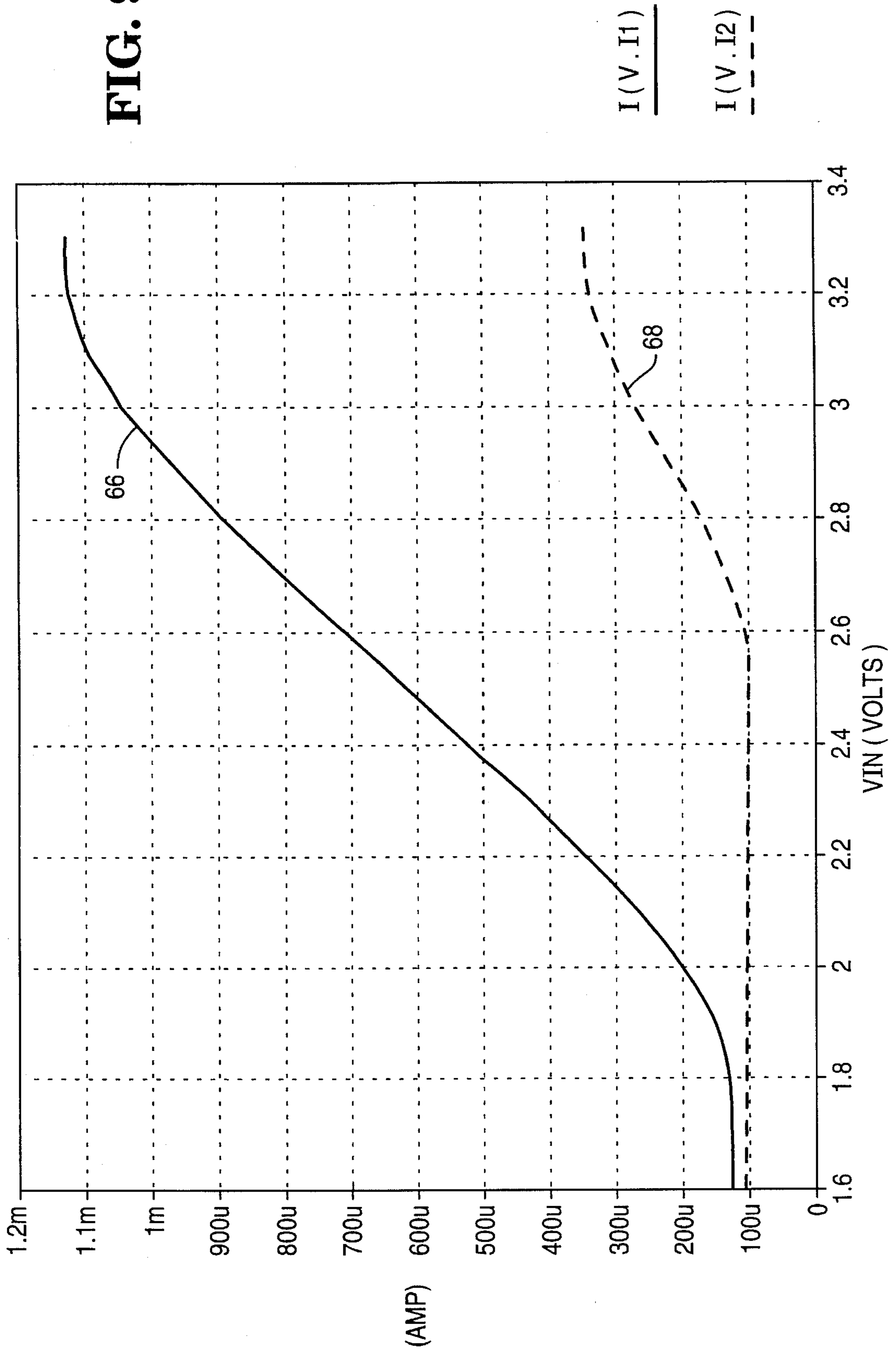
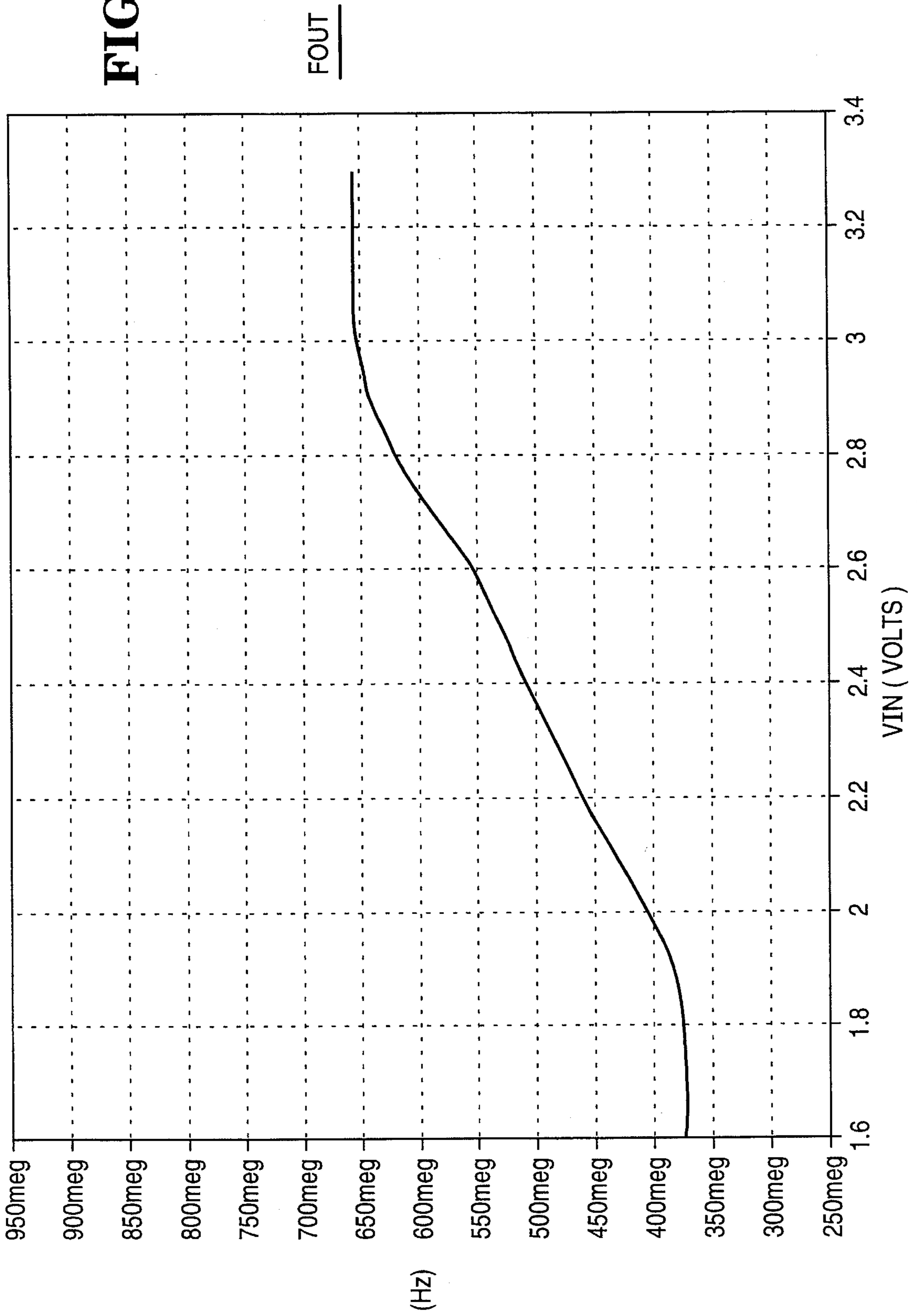


FIG. 10



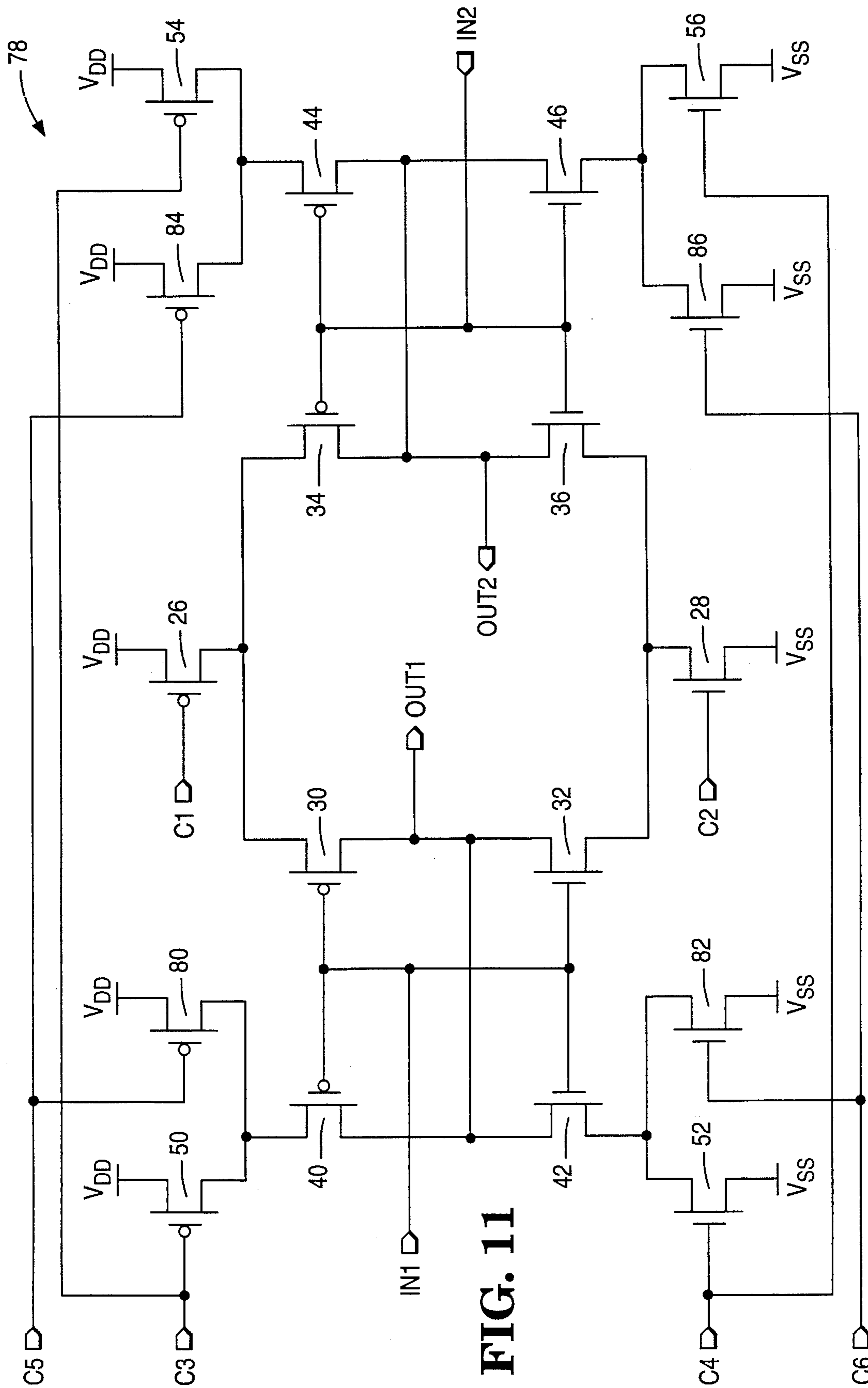


FIG. 12A

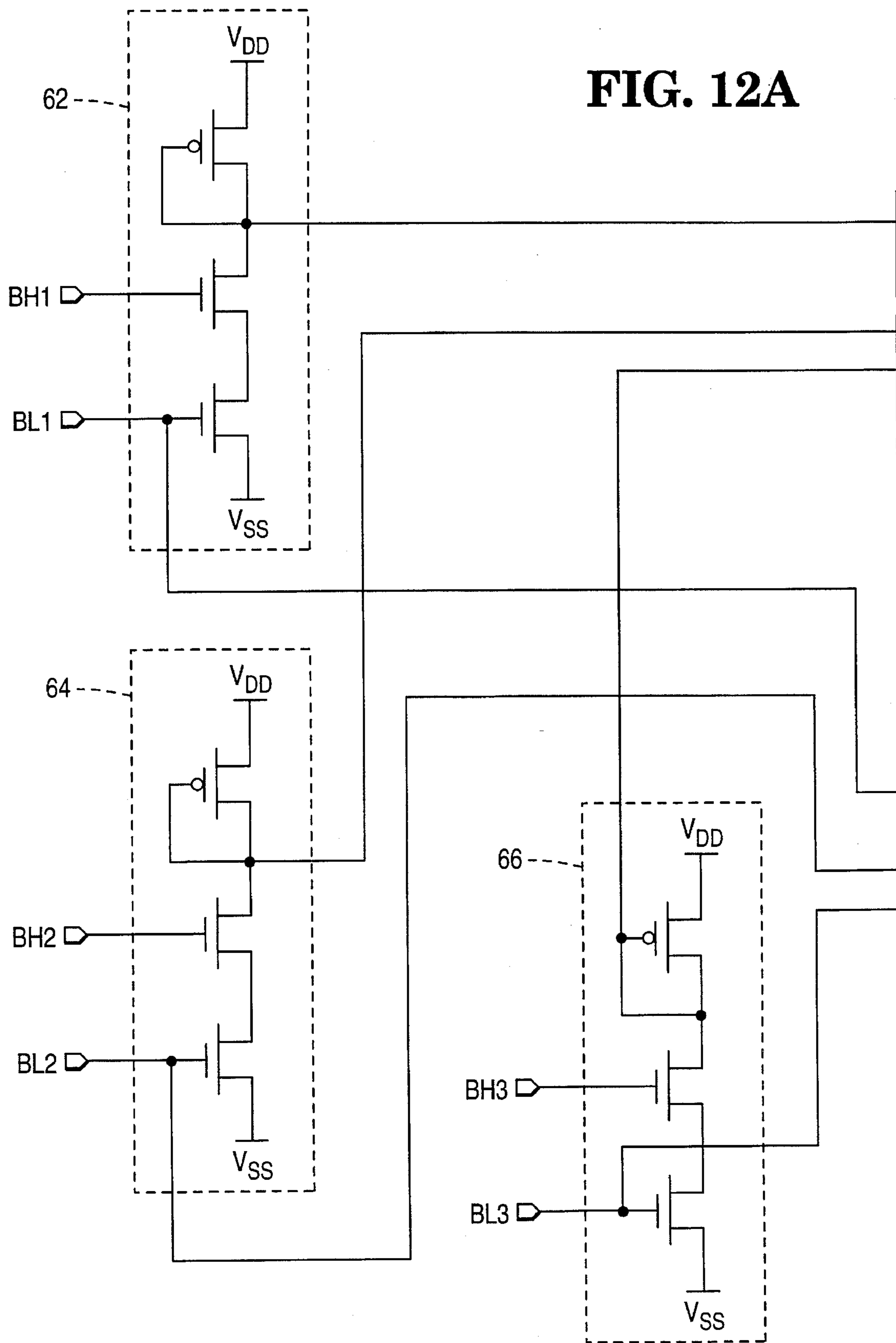


FIG. 12B

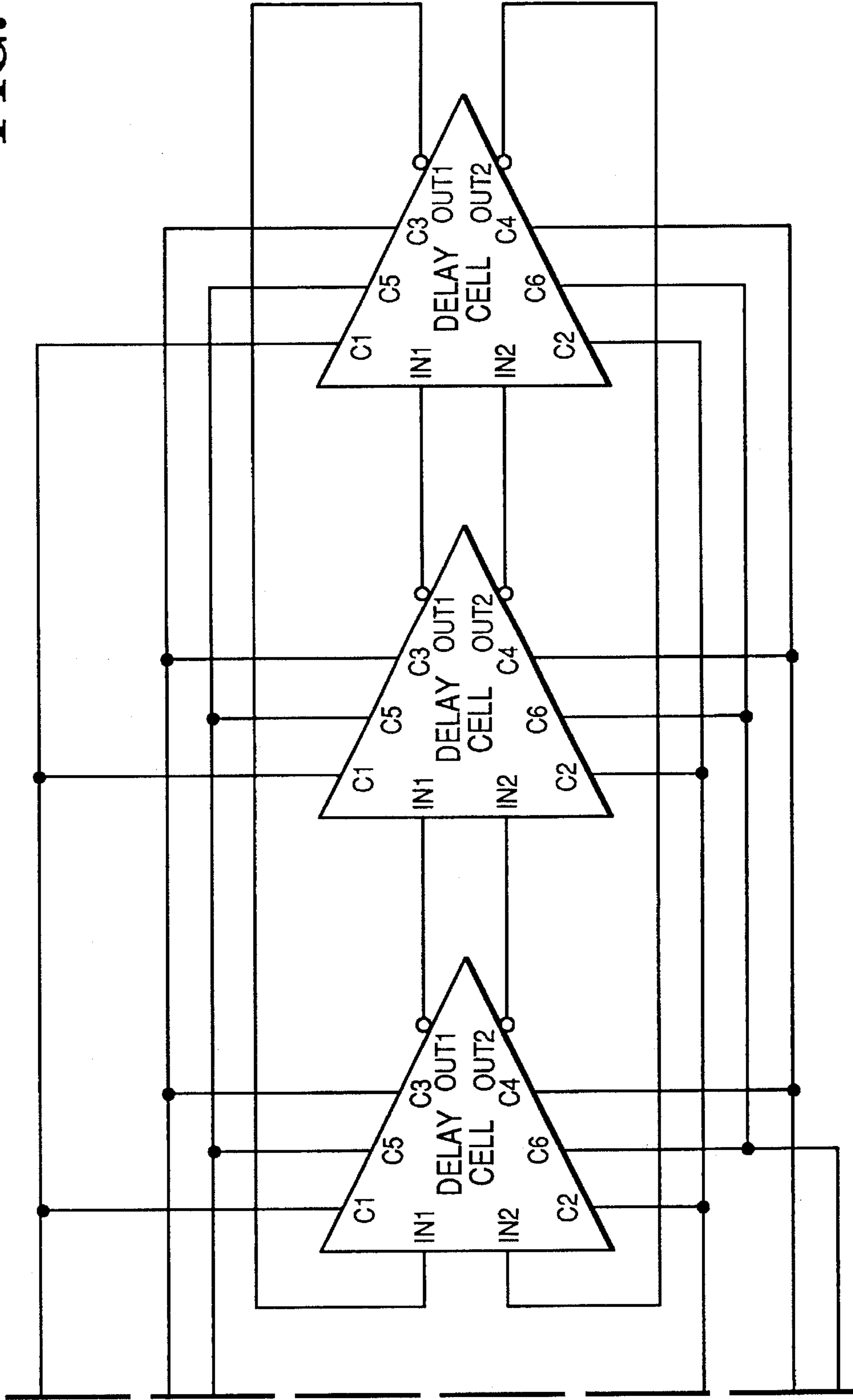


FIG. 13A

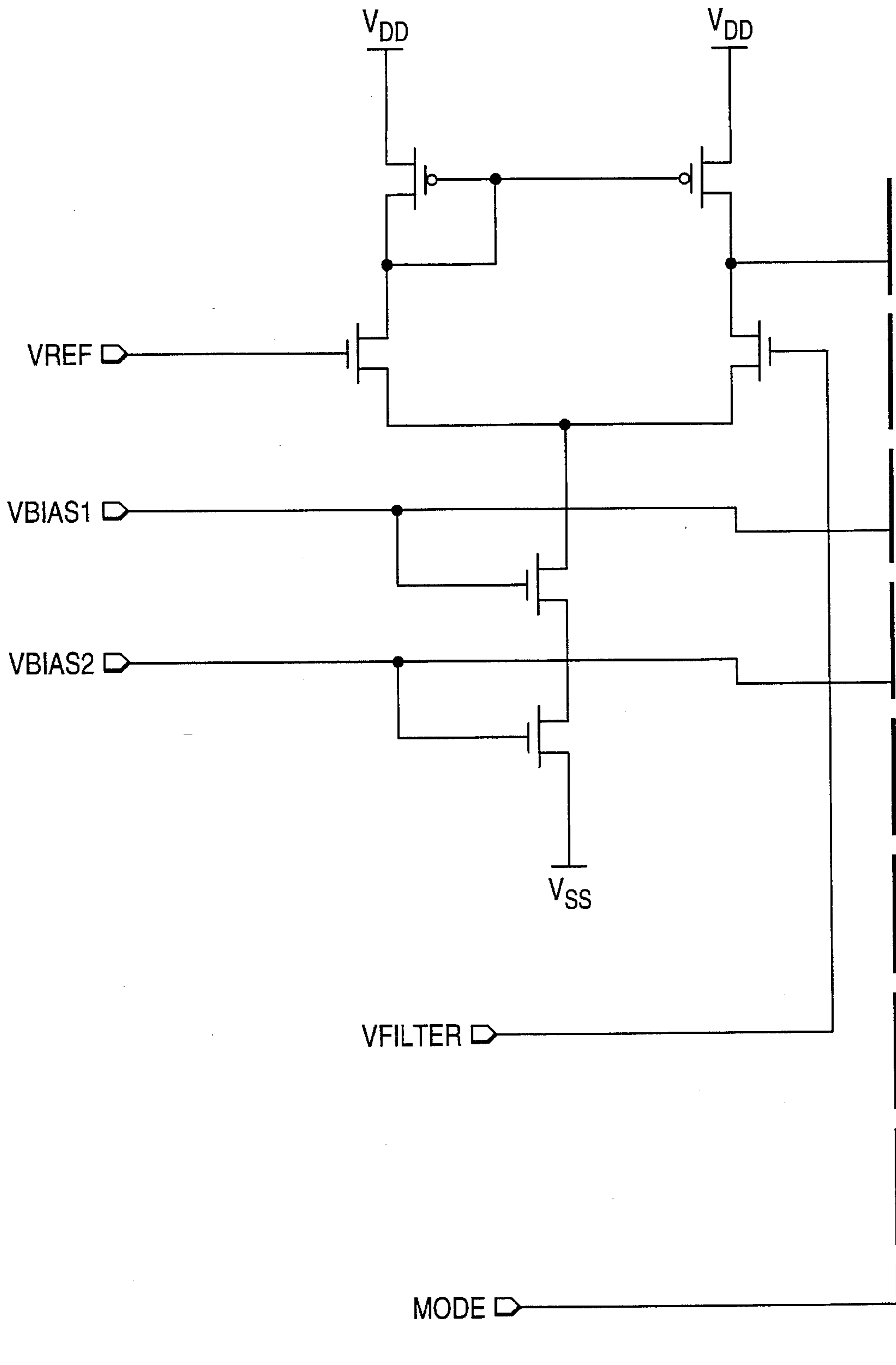


FIG. 13B

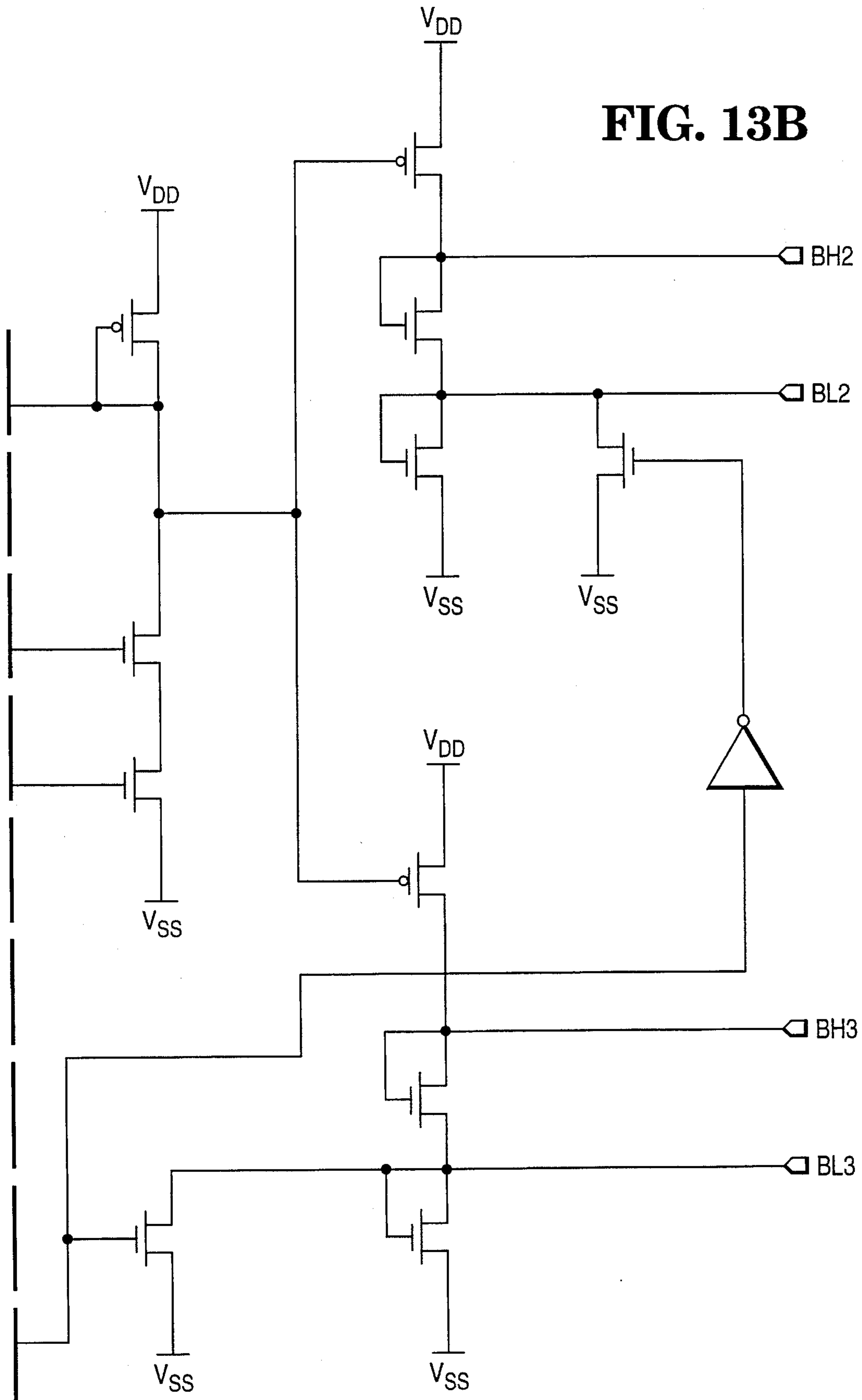


FIG. 14

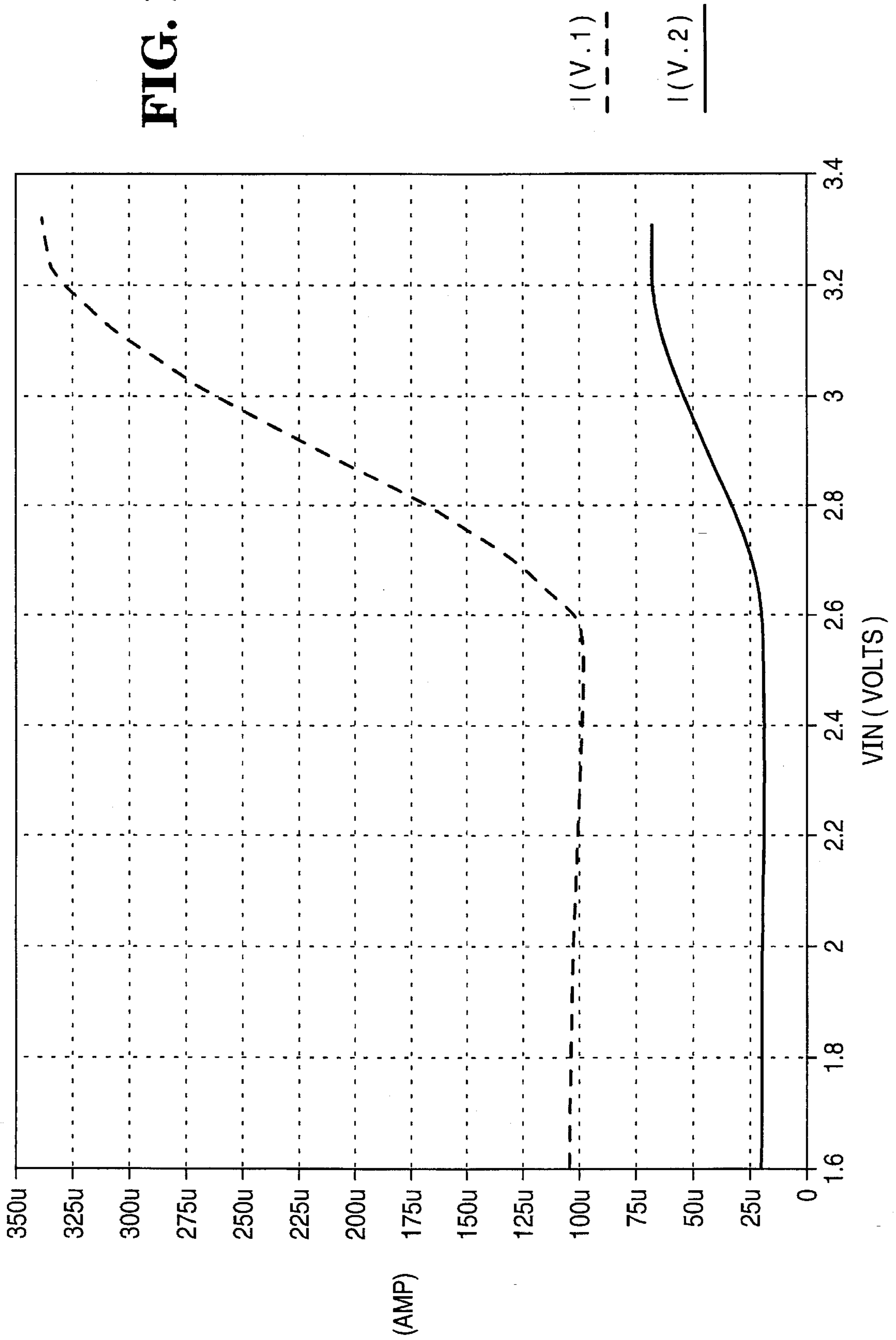
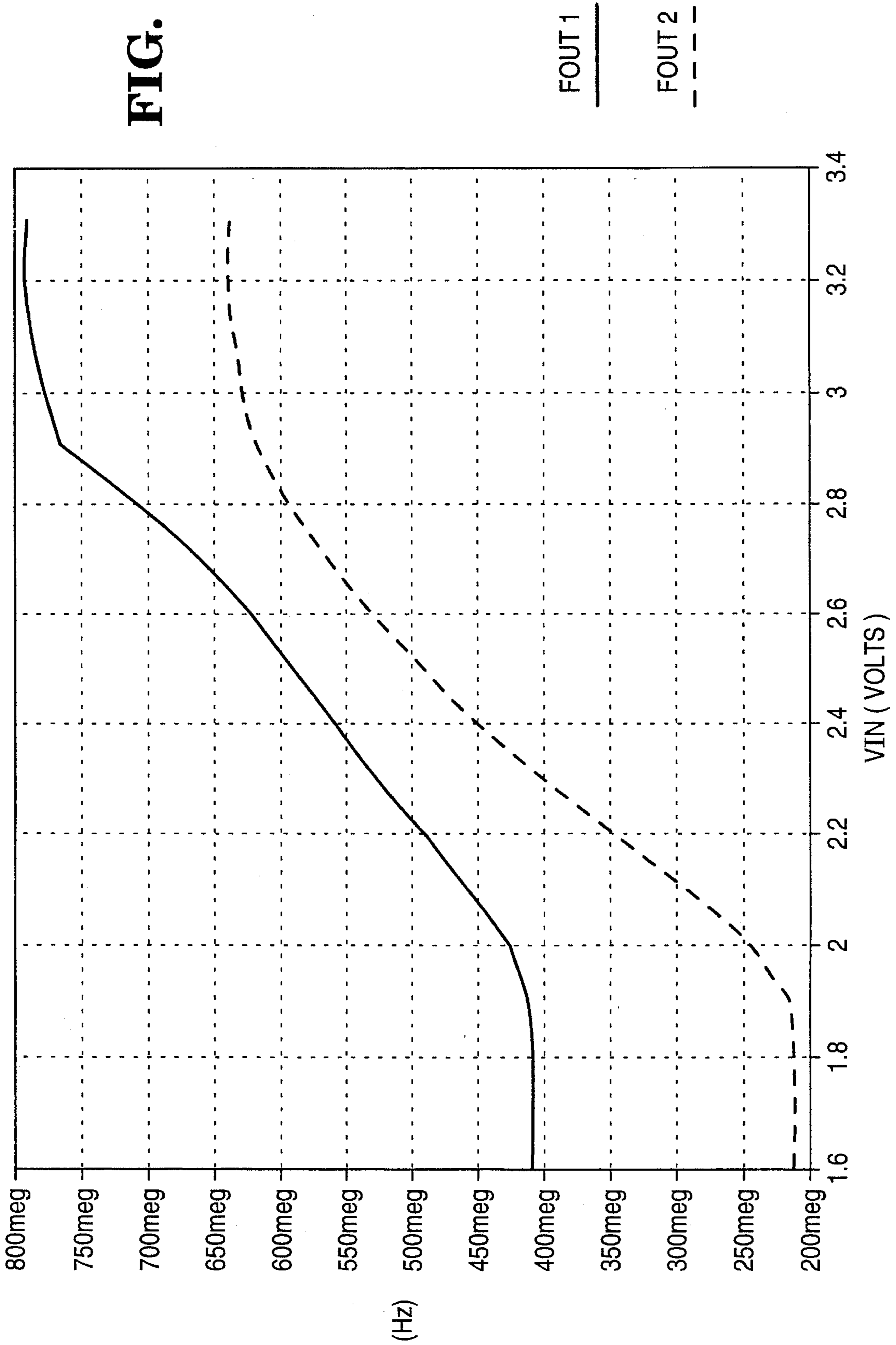


FIG. 15



EXTENDIBLE-RANGE VOLTAGE CONTROLLED OSCILLATOR

CROSS REFERENCE TO RELATED APPLICATIONS

The present invention is related to commonly assigned and co-pending U.S. application entitled "Multi-Range Voltage Controlled Oscillator", invented by Anderson and Schmitt, having a Ser. No. 08/264,862 and filed concurrently herewith; and pending U.S. application entitled "Bias Compensation for a Voltage Controlled Oscillator", invented by Anderson, having a Ser. No. 08/264,815 and filed concurrently herewith; and both of which are hereby incorporated by reference.

1. Technical Field

The present invention relates to high speed circuit operation, and more particularly to a way for improving the operating characteristics of a phase-locked loop integrated circuit.

2. Background of the Invention

High-speed serial links are becoming more common, replacing bulkier parallel connectors. Speeds for these high-speed serial links vary according to differing industry standards. Serial interface chips generally require the use of a phase-locked loop (PLL) to generate a clock for data transmission, and another PLL for data reception.

Fast PLL circuits employ fast voltage controlled oscillators (VCO). The operating speed of the VCO determines what frequencies the serial interface chips will operate. Different operating speeds are accomplished by frequency division and multiplication. However, if an operating speed cannot be achieved through frequency division and multiplication, an additional VCO must be incorporated into the design. The chip could be programmed to operate at the different operating speeds by choosing the appropriate oscillator.

In reality, only a couple of the operating speeds can be achieved using frequency division and multiplication. VCO ranges are only so large, and adding an additional VCO complicates design and uses more silicon area. A simpler solution would be to have a single VCO that would operate in different frequency ranges. Having the ability for one integrated circuit chip to achieve several operating speeds would also be beneficial.

The operating range of a VCO (i.e. the range of possible output frequencies for a particular range of input voltages) is another important aspect to consider when designing a fast PLL circuit. One way to implement a VCO is by use of a ring oscillator. Ring oscillators can be derived from cascaded delay cells. The number of delay cells, and the delay time of each delay cell, determines the operating frequency. The delay time of the delay cell can vary with temperature, supply voltage and process, sometimes pushing the operating range far from the desired operating point.

In phase-locked loop applications, voltage controlled ring oscillators with starved inverter delay cells are sometimes used when designing CMOS integrated circuits. Using booster inverters in parallel with the starved inverter delay cells results in a faster operating frequency. However, the frequency range is limited at the low end of the frequency range due to the booster inverter. There is a tradeoff between how large the booster inverter is and how high the frequency range is, and how small the booster inverter is and how low the frequency range is. In summary, the addition of a booster

inverter increases the speed of the oscillator, but limits the frequency range of the oscillator.

When designing high frequency VCOs, frequency drift (from the desired operating point) due to process variation can cause a low yield. If the frequency range could be extended to obtain overlap between process variations, a higher yield could be obtained.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an improved VCO.

It is a further object of the present invention to provide a multi-range VCO.

It is yet another object of the present invention to provide an extendible-range VCO.

The present invention is an improved VCO having plural operating ranges. This multi-range VCO design has the ability to operate at two or more operating ranges, thus enhancing the ability to manufacture high-speed serial links with several operating speeds. By modifying the ring oscillator delay cells, more than one operating speed can be achieved. By adding current sources to the booster inverters, and selectively scaling this current, the frequency range of the delay cells can be significantly altered, resulting in a multi-range VCO.

A linear, wide-range VCO is also provided by the present invention. This design allows the frequency range of a VCO to be extended, and adds a circuit to linearize the response. In addition, it reduces the VCO's response to process variation.

BRIEF DESCRIPTION OF THE DRAWING

FIG. 1 shows a traditional phase-locked loop circuit.

FIG. 2 shows a ring oscillator constructed using delay cells.

FIG. 3 shows a differential current starved inverter.

FIG. 4 shows a delay cell comprising a main current starved inverter and a booster inverter.

FIG. 5 shows a delay cell comprising a main current starved inverter and a current controlled booster inverter.

FIG. 6 shows a realized circuit schematic for the delay cell of FIG. 5.

FIG. 7 shows an improved ICO.

FIG. 8 shows a voltage to current converter circuit.

FIG. 9 shows a response plot for two voltage-to-current converters.

FIG. 10 shows the frequency response curve for an improved VCO.

FIG. 11 shows a delay cell for a multi-range VCO, where booster inverter current sources have scaled current biasing.

FIGS. 12A-B show a multi-range ICO using a plurality of delay cells as depicted in FIG. 11.

FIGS. 13A-B show a voltage to current converter with current scaling.

FIG. 14 shows a response plot of voltage to current converters with current scaling.

FIG. 15 shows simulation results of a multi-range VCO.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

The block diagram for a typical phase-locked loop is shown at 10 in FIG. 1. The input reference phase 12 is

compared at 18 to the output 14 of the VCO 23. The charge pump 19 regulates the amount of charge on the loop filter 20. The output 22 of the loop filter 20 is a voltage that controls the frequency of the oscillator 23. A VCO 23 typically consists of two stages: a voltage to current (V-I) converter, and a current controlled oscillator (ICO). The VCO output frequency varies proportionally to the input voltage of the V-I converter.

Oscillator 23 typically contains a current controlled oscillator 16, as shown in FIG. 2. The ICO has an odd number of delay cells. Each delay cell 24 is essentially a current controlled inverter. Since there is an odd number of delay cells, the delay cells are constantly changing state at a speed determined by the propagation delay of each cell. By varying the current in the delay cell, the propagation delay of each cell is varied, and thus the frequency of the ICO is varied.

A detailed schematic for one of the delay cells of FIG. 2 is shown in FIG. 3. The delay cell is a current starved differential inverter 24. The starved inverter current is biased at 26 and 28 by a V-I converter (not shown), whose output is mirrored to inputs C1 and C2. As the input voltage of the V-I converter increases, the mirrored inverter current in the delay cell increases, which in turn increases the operating speed of the oscillator.

More specifically, signals IN1 and IN2 are two inverter inputs, and signals OUT1 and OUT2 are two inverter output signals, of differential inverter 24. N-FET and P-FET transistors 30 and 32 provide an inverted signal from input IN1 to output OUT1. Similarly, N-FET and P-FET transistors 34 and 36 provide an inverted signal from input IN2 to output OUT2. Inputs IN1 and IN2 are 180 degrees out of phase with respect to each other. Similarly, outputs OUT1 and OUT2 are 180 degrees out of phase with respect to each other. Control inputs C1 and C2 vary the current through the inverter, and thus the propagation delay of the delay cell is varied. This in turn varies the frequency of the oscillator. In particular, P-FET 26 acts as a current source, and is regulated by the input C1. Similarly, N-FET 28 acts as a current source, and is regulated by the input C2. An increase in the bias current in the delay cell results in faster operation of the inverter, and hence a VCO operating at a higher frequency.

By incorporating a booster inverter to the main current starved inverter, a more robust delay cell is achieved. This improved delay cell is illustrated at 38 in FIG. 4. The booster inverter is comprised of four FET transistors 40, 42, 44 and 46. The booster inverter transistors increase the frequency of the oscillator. A balance must be found between the strength of the main starved inverter and the booster inverter. As the strength of the booster inverter is increased, the frequency range of the VCO is shifted to a higher frequency. As the strength of the booster is decreased, the frequency range of the VCO is shifted to a lower frequency. With proper device sizing, a balance between frequency and linearity can be achieved. However, if a wider frequency range is required, this arrangement is insufficient. The addition of the booster inverters increases the speed of the oscillator, but limits the frequency range.

Extendible-Range VCO

To achieve a wider frequency range of operation, a plurality-of voltage controlled current sources are implemented to restrict the current in the booster inverters, as shown in FIG. 5. This implementation achieves three desirable effects. First, the current sources 50, 52, 54 and 56 restrict current through the booster inverters, thus reducing power consumption.

Second, the reduced current helps to minimize the effects of process variation. That is, a best case inverter when

connected directly to Vdd and Vss would draw more current than a worst case inverter, which in turn affects propagation delay. With the use of a current source, the current is kept constant. The constant current in the booster inverters reduces the sensitivity of the delay cell to process variation. With a constant current, the propagation delay does not vary as much, thus a reduced sensitivity to process variation.

Third, the VCO can be controlled to lower frequencies. For example, if we size the inverter devices to achieve the shortest propagation delay, the current controlled capability of the booster circuits allows the delay cell current to be starved in both the main starved inverter and the booster inverter. Thus, a lower frequency is achievable. Yet, a short propagation delay still exists for high frequency operation. This results in a VCO with a wide or extended range of operation.

The circuit realization for delay cell 58 of FIG. 5, including the devices for the voltage controlled current sources 50, 52, 54 and 56, as well as for the voltage controlled current sources 26 and 28, is shown in FIG. 6. Current source 26 is biased by input C1, and current source 28 is biased by input C2. Current sources 50 and 54 are biased by input C3, and current sources 52 and 56 are biased by input C4.

A schematic for the improved current controlled oscillator 60 is shown in FIG. 7. Note the two bias circuits 62 and 64, which are needed to drive the inputs labeled C1, C2, C3 and C4 in FIG. 7. The control of these current mirror bias circuits 62 and 64 will be further described below.

The next challenge is to decide how to bias the booster inverter current sources 50, 52, 54 and 56 of delay cells 58. If they are biased similarly to the main starved inverter, a nonlinear response is obtained. If they are held constant, a reduced frequency range is obtained. To overcome this drawback, a piece-wise linear biasing scheme is adapted. For example, the current of the booster inverters is held constant at lower frequencies reducing the nonlinear response at the low end. At higher frequencies where the response would normally roll-off, the booster inverters are linearly increased, thus increasing the range, and linearizing the circuit.

To accomplish voltage control of the current controlled oscillator, two V-I converters are used; one for the main starved inverter 24, and one for the booster inverter current sources 50, 52, 54 and 56. The outputs of these two V-I converters are coupled, respectively, to the current mirrors 62 and 64 shown in FIG. 7. Current mirror 62 is controlled by inputs BH1 and BL1, and current mirror 64 is controlled by inputs BH2 and BL2. The preferred V-I converter for providing one set of BH and BL current mirror inputs is shown in FIG. 8. In the example shown, outputs BH and BL are generated for inputs BH1 and BL1 of current mirror 62. A duplicate V-I converter circuit (hereinafter the booster V-I converter) is used to generate current mirror inputs BH2 and BL2 for current mirror 64.

The current bias for the circuit in FIG. 8 is derived from a typical band gap voltage reference commonly known in the art, and mirrored to inputs VBIAS1 and VBIAS2. Input VREF is set at a static DC voltage, preferably 2.5 volts for the main V-I converter and 2.9 volts for the booster V-I converter. Input VFILTER is the loop filter output voltage, as indicated at 22 of FIG. 1.

A plot of the current control response of both the main starved inverter and the booster inverter is shown in FIG. 9. The solid curve 66 is the main starved inverter V-I curve. As shown at 68, the booster inverter current sources are kept constant for the lower frequencies. The booster V-I converter is designed, by selecting appropriate device sizes using

techniques commonly known in the art, such that the booster inverters are linearly turned on at approximately 2.6 volts (as shown by the dotted curve **68** in FIG. **9**), to extend and linearize the-response just before the main starved inverters would otherwise roll-off (i.e. where an increase in current results in minimal increase in frequency).

The response of the complete VCO, containing the V-I converters and the current controlled oscillator with the enhanced delay cell, is shown in FIG. **10**. Note that the oscillator range is approximately 285 MHz (370 MHz -655 MHz). Compared with a similar ring oscillator designed in the same technology which is 200 MHz, we note an approximate increase in range of approximately 30%. In summary, this response is achieved by adding current sources to the booster inverters, and controlling them in such a way as to linearize the resulting response over a broad frequency range.

Multi-Range VCO

An additional operating range can be achieved by scaling the current in the booster inverter current sources **50**, **52**, **54** and **56**. That is, by scaling the current in the booster inverters, the frequency range can be significantly altered, thus achieving multi-range operation. The actual delay cell circuitry for this multi-range VCO is shown in FIG. **11**. There are four extra devices added to the previously described delay cell of FIG. **6**. The extra devices **80**, **82**, **84** and **86** are the four current sources needed to change/scale the booster inverter bias. In the preferred embodiment, only one pair of current sources is on at a time, by either activating inputs **C3** and **C4**, or by activating inputs **C5** and **C6**. However, the current sources could all be on or off, further modifying the operating frequency range of the delay cell/VCO. The complete current controlled ring oscillator with multi-range capability is shown in FIGS. **12A-B**.

For this circuit in FIGS. **12A-B** to work properly, an extra current mirror **66** is needed. This additional current mirror requires another output from the booster V-I converter. The preferred embodiment for this booster V-I converter with additional current mirror is shown in FIGS. **13A-B**. This circuit works similarly to the circuit in FIG. **8**, except that a choice can be made to select the appropriate current mirror with the **MODE** input. This **MODE** input of the V-I converter insures that only one current mirror is on at a time. The **MODE** input is a digital input that is controllable by a user. Any type of device capable of generating digital output signals, such as a custom control circuit, microcontroller, or other programmable device having output signals, could drive the **MODE** input signal.

The plot in FIG. **14** illustrates how the current in the booster inverters are being modulated by the input voltage. The larger current (as indicated by the dotted line) is for the faster response. The current through the main starved inverter is linearly swept, as was previously described with respect to the output current **66** in FIG. **9**. If a wide frequency range is not required, the current in the booster inverters can be kept constant across the whole range, and then scaled for different operating ranges.

FIG. **15** shows the transfer characteristic of the multi-range ring oscillator using the improved delay cell described hereinabove. The plot is output frequency versus input voltage. The results illustrate how that, by selecting the different current mirrors, two different operating ranges can be achieved. Note the significant frequency shift in the transfer characteristic (i.e. the difference between the dotted and solid lines) when the current through the booster inverters is scaled to a different value. The frequency shift at mid-range is approximately 100 MHz. The gain of each plot

is approximately the same. This is an important point, since loop stability could be compromised if the VCO gain is significantly varied.

While I have illustrated and described the preferred embodiments of our invention, it is to be understood that I do not limit myself to the precise constructions herein disclosed, and the right is reserved to all changes and modifications coming within the scope of the invention as defined in the appended claims.

We claim:

1. An extended range voltage controlled oscillator, comprising:

a plurality of delay cells with booster inverters;

a current source which restricts current in at least one of the booster inverters; and

a bias circuit for piece-wise linearly biasing the current source.

2. The oscillator of claim **1** further comprising a plurality of voltage-to-current controlled converters.

3. The oscillator of claim **2** wherein a first voltage-to-current controlled converter is operatively coupled to at least one of the plurality of delay cells.

4. The oscillator of claim **2** wherein a second voltage-to-current controlled converter is operatively coupled to at least one of the booster inverters.

5. An improved phase-locked loop circuit, comprising:

a phase detector;

a charge pump operatively coupled to the phase detector;

a filter operatively coupled to the charge pump; and

an oscillator operatively coupled to the filter, wherein the oscillator comprises (i) a plurality of delay cells with booster inverters; (ii) a controllable current source which restricts current in at least one of the booster inverters; and (iii) a bias circuit for piece-wise linearly biasing the controllable current source.

6. The oscillator of claim **5** further comprising a plurality of voltage-to-current controlled converters.

7. The oscillator of claim **6** wherein a first voltage-to-current controlled converter is operatively coupled to at least one of the plurality of delay cells.

8. The oscillator of claim **6** wherein a second voltage-to-current controlled converter is operatively coupled to at least one of the booster inverters.

9. A method for extending an operating range of a phase-locked loop circuit comprising a plurality of delay cells, the method comprising the steps of:

controlling current in a booster inverter of at least one of said delay cells; and

piece-wise linear biasing the booster inverter.

10. The method of claim **9** wherein the current in the booster inverter is restricted.

11. The method of claim **9** wherein the step of piece-wise linear biasing the booster inverter comprises maintaining a constant current in the booster inverter at relatively low frequencies, and linearly increasing current in the booster inverter at relatively high frequencies.

12. In combination:

a booster inverter; and

means for maintaining a constant current in the booster inverter at relatively low frequencies, and linearly increasing current in the booster inverter at relatively high frequencies.